

Neutrinos, WMAP, and BBN

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New data from WMAP have appeared, related to both the fractional energy density in relativistic species at decoupling and also the primordial helium abundance, at the same time as other independent observational estimates suggest a higher value of the latter than previously estimated. All the data are consistent with the possibility that the effective number of relativistic species in the radiation gas at the time of Big Bang Nucleosynthesis may exceed the value of 3, as expected from a CP-symmetric population of the known neutrino species. Here we explore the possibility that new neutrino physics accounts for such an excess. We explore different realizations, including neutrino asymmetry and new neutrino species, as well as their combination, and describe how existing constraints on neutrino physics would need to be relaxed as a result of the new data, as well as possible experimental tests of these possibilities.

INTRODUCTION

One of the remarkable successes of Big Bang Nucleosynthesis (BBN) is the correct prediction of the overall magnitude of the light element abundances as a function of two fundamental parameters: the baryon density in the universe, and the number of light neutrino species. Until recently BBN provided the only direct handles on these two fundamental parameters (i.e. [1–3]). However with the discovery of primordial anisotropies in the Cosmic Microwave Background (CMB) radiation, the CMB has become a remarkable precision laboratory to constrain fundamental parameters in particle physics and cosmology. It can now be used to test various ideas associated with BBN, and consistency checks can be applied to probe new physics.

It is therefore of some interest that recent results from both of these areas suggest the possibility the some new physics beyond the standard model may be at play. Izotov and Thuan [4] have recently analyzed the primordial helium abundance. For the primordial ^4He mass fraction, Y_p , they find $Y_p = 0.2565 \pm 0.0010(\text{stat.}) \pm 0.0050(\text{syst.})$, which is higher, at the 2σ level, than previous measurements (see e.g. [5] and references therein.) Note that this value is in good agreement with another recent estimate [6] although their quoted error is far smaller. At the same time the new WMAP 7 year analysis [7] suggests both a high value of Y_p (with larger error bars), and independently a somewhat high value of the N_{eff} , the effective number of relativistic neutrino species present during last scattering ($N_{eff} = (\rho_{rel} - \rho_\gamma)/\rho_{\nu_{therm}}$, where $\rho_{\nu_{therm}} = (7\pi^2/120)(4/11)^{4/3}T_\gamma^4$). Specifically, the WMAP 7 measurement is $N_{eff} = 4.34 + 0.86 - 0.88$ [8], about 1.4σ higher than the standard contribution of the known neutrino species, $N_{eff}=3$.

While the uncertainties in these estimates remain

large, if confirmed experimentally in the future, a scenario with high Y_p and high N_{eff} would be an interesting challenge for particle physics. While multiple, uncorrelated, phenomena could explain it, both the Izotov and Thuan and the WMAP 7 results are clearly consistent with a single physical cause: that number of helicity degrees of freedom in the radiation gas at the time of BBN might have been significantly higher than 3. The simplest and most conservative possibility for this involves new neutrino physics.

Within the context of neutrino physics alone, two different possibilities arise. One can consider mechanisms which affect both the energy density of neutrinos during BBN and the weak interaction rates that determine equilibrium nuclear abundances, such as would be the case for a neutrino-antineutrino asymmetry. As a more minimal option, a correlation between two phenomena that are very separated in cosmic time—an elevated helium abundance after BBN ($T \sim 0.2$ MeV) and extra energy density in relativistic degrees of freedom at matter-radiation decoupling ($T \sim 0.1$ eV)—could have a common origin in an overabundance of weakly interacting and light (sub-eV) mass particles at the time of BBN. During BBN this overabundance enhances the energy density, which, as we have alluded, in turn increases the expansion rate of the universe. This causes the weak reactions to freeze out earlier, resulting in a higher neutron-to-proton ratio and therefore a higher Y_p [2, 9–15]. Depending on their coupling to matter, the same particles could also affect Y_p by contributing to the weak reaction rates. At matter-radiation decoupling, they could still be relativistic and therefore contribute to N_{eff} as measured by WMAP7. Other possibilities will also be briefly discussed. Previous strong constraints on both weak interaction physics and neutrino flavors need to be relaxed as a result of the current data, allowing possibilities that had previ-

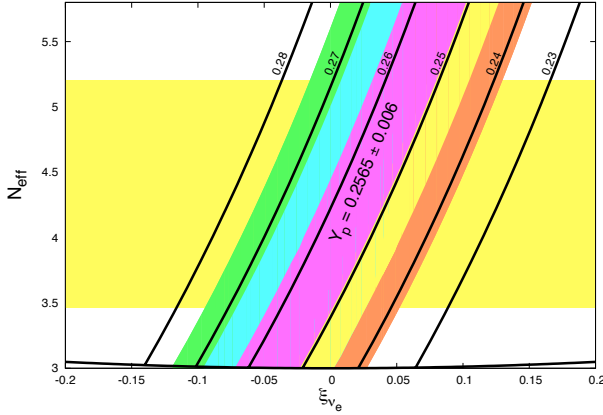


FIG. 1: Y_p contours in the ξ_{ν_e} and N_{eff} parameter space assuming neutrino flavor equilibration ($\xi_{\nu_e} = \xi_{\nu_\mu} = \xi_{\nu_\tau}$). The horizontal light (yellow) band corresponds to the 1σ WMAP 7 year result. The black contours show a range of calculated values of Y_p given model independent inputs of ξ_{ν_e} and N_{eff} . The shaded (colored) vertical bands mark the Izotov and Thuan 1σ , 2σ , and 3σ ranges of Y_p . The bottom black curve shows the contribution to N_{eff} from neutrino asymmetries alone.

ously been considered as ruled out.

Clearly, suitable candidates should fit a number of conditions: (1) they should couple to matter and radiation strongly enough to be produced by thermal processes before BBN but (2) should not contribute too many extra degrees of freedom to the radiation gas, constrained in turn by measurements of Y_p . Furthermore, (3) they are constrained by the existing cosmological bounds on the density of light extra degrees of freedom coming from a combination of data from the CMB, Large Scale Structure (LSS), Lyman Alpha Forest, and Baryon Acoustic Oscillations [8]: $\Omega_\nu h^2 < 0.006$ (95% CL). We consider specific scenarios and constraints in the following sections.

NEUTRINO ASYMMETRIES AND DECAYS

An overabundance of neutrinos with respect to anti-neutrinos or vice-versa, $L_\nu \equiv (n_\nu - n_{\bar{\nu}})/n_\gamma$, is defined by a non-zero degeneracy parameter, ξ : $L_\nu = \pi^2/(12\zeta(3))(T_\nu/T)^3(\xi + \xi^3/\pi^2)$. The total change in the effective number of relativistic species resulting from asymmetries in each flavor, ξ_{ν_α} , is given by

$$\Delta N_{eff} = \sum_{\alpha=e,\mu,\tau} \left[\frac{30}{7} \left(\frac{\xi_{\nu_\alpha}}{\pi} \right)^2 + \frac{15}{7} \left(\frac{\xi_{\nu_\alpha}}{\pi} \right)^4 \right]. \quad (1)$$

In most theoretical scenarios, lepton and baryon asymmetries are enforced to be of the same order by sphalerons [16], so that $L_\nu \sim 10^{-10} - 10^{-9}$. However, several scenarios have been proposed in which a large lepton asymmetry can be generated while preserving a small baryon asymmetry, using e.g., GUT models, the Affleck- Dine mechanism, Q-balls, resonant oscillations, etc. [17–22]. Therefore, here we assume L_ν as independent from the baryon asymmetry and consider only direct constraints on it from neutrino physics.

While asymmetries in all flavors contribute to an increase in energy density, only an asymmetry in the electron flavor influences the weak neutron-proton interconversion processes. For this reason, the sensitivity of BBN to ξ_{ν_e} is remarkably high: $|\xi_{\nu_e}| \lesssim \text{few } 10^{-2}$ is needed for compatibility with measured abundances (see e.g.[3, 14, 15, 23–27]). This applies also to the asymmetries in the other flavors at the time BBN, since oscillations should produce an at least approximate flavor equilibration before BBN [28–31].

Under such strong constraint, neutrino asymmetries alone generally cannot account for a $\Delta N_{eff} \sim 1$. An interesting exception is the somewhat fine-tuned scenario of initial (pre-equilibration) flavor asymmetries that are large and opposite in sign. After equilibration, a surviving $\Delta N_{eff} \sim 1$ can be realized, together with sufficiently small asymmetries that satisfy BBN bounds [32]. This reopens the possibility of having, at BBN, virtually any combination of ξ_{ν_α} and energy density. In general, asymmetries could coexist with other effects (e.g., a sterile neutrino, see next section) that could independently increase N_{eff} . Therefore an analysis that treats asymmetries and energy density as independent is necessary to find the most general constraints on both.

Here we perform such a study, using a modified version of the Kawano/Wagoner BBN code described in detail in Ref. [13, 33]. In Fig. 1 we illustrate the interplay between asymmetries and N_{eff} by plotting the Y_p abundance yield isocontours in the $N_{eff} - \xi_{\nu_e}$ parameter space. This figure shows calculations for model-independent inputs of N_{eff} over a wide range of neutrino asymmetries, where we have adopted the condition of neutrino equilibration of asymmetries, so that the allowed range of asymmetries is small, and the direct effect of such asymmetries on N_{eff} is minimal (as displayed in the lower curve, which shows the extra direct contribution to N_{eff} from such asymmetries). The horizontal band for N_{eff} corresponds to the 1σ WMAP 7 year result quoted earlier.

The BBN code used to make Fig. 1 differs from others in a number of ways, mostly in the treatment of the weak processes. It allows for calculations that include both the effects from higher relativistic degrees

of freedom and neutrino asymmetries, which is not the case for the Kawano/Wagoner code. This code gives a standard BBN Y_p yield that is ~ 0.004 lower than other calculations due to the full numerical integration of each weak reaction rate. This figure is not intended to provide new constraints on, or a best fit for, neutrino asymmetries and/or N_{eff} . It is simply a model-independent tool to illustrate the fact that a wider range of allowed N_{eff} parameter space loosens the BBN limit on the neutrino asymmetries or lepton numbers.

This figure demonstrates explicitly the (known) fact that the neutrino electron degeneracy parameter has significant leverage on Y_p . Positive ξ_ν drives the neutron destruction process, $\nu_e + n \rightleftharpoons p + e^-$ forward and Pauli-blocks the reverse neutron production reaction resulting in a lower Y_p . Negative ξ_ν , corresponding to an overabundance of anti-neutrinos, drives anti-neutrino capture forward $\bar{\nu}_e + p \rightleftharpoons n + e^+$ and suppresses the reverse proton production reaction resulting in more helium. This figure displays explicitly the novel recognition that to obtain a given isocontour for Y_p , one can increase ξ_ν while also increasing N_{eff} , and it provides a quantitative estimate of the interplay between these effects. This interplay has not been directly examined quantitatively before, although a correlation between the two parameters was noted in a fit to BBN data [26] and in an analysis of the baryon-to-photon ratio [14].

The figure also shows how the constraints on ξ_{ν_e} change with a change of N_{eff} and can thus be relaxed compared to previous limits. For example, if we allow N_{eff} in the 1σ WMAP7 interval and Y_p in the 3σ interval of Izotov and Thuan we get an approximate allowed range of

$$-0.14 \lesssim \xi_{\nu_e} \lesssim 0.12, \quad (2)$$

larger than the usually quoted constraint $-0.04 \leq \xi_{\nu_e} \leq 0.07$ [23]. While these results present a model-independent exploration of parameter space, with each point involving a full BBN code calculation of Y_p for a given value of N_{eff} and ξ , whether any specific point in parameter space is actually realizable however, will depend upon specific model building issues.

We conclude this section by briefly mentioning another possibility for adding extra relativistic energy density both during BBN times and during the matter-radiation equality epoch: extra particles that are unstable. To produce higher Y_p , these particles must contribute to the relativistic energy density during the “weak freeze out” period in BBN, implying masses $m \leq 1$ MeV. They would then be required to decay by the time of matter-radiation equality ($T \sim 1$ eV), where the CMB measurements infer extra relativistic

degrees of freedom (see for example [34, 35]).

However, additional cosmological constraints imply that the physics of such particles is so finely tuned as to be implausible. Their decay can only be into neutrinos so as not to produce high-energy photons which result in subsequent deuterium photo-disassociation [36]. Furthermore, the additional particles must decay quickly enough so that they don’t subsequently dominate the energy density of the universe once the temperature falls below their mass. The dual requirements of being primarily weakly interacting and also decaying within the appropriate time window are extremely difficult to satisfy.

STERILE AND RIGHT HANDED NEUTRINOS

The minimal scenario to explain both high N_{eff} and high Y_p with neutrino physics is a light sterile neutrino (see also [37]). Indeed, sterile neutrinos easily fit the conditions we have outlined above: by definition they are weakly interacting, they can be produced before BBN, and they are allowed, by laboratory and astrophysical bounds, to be of sub-eV mass.

Specifically, if the neutrino masses come from a See-Saw-like mechanism, active-sterile oscillations arise naturally due to the mixing of active neutrinos with the charge-conjugate of one or more right handed neutrinos. Depending on the mixing and masses, the interplay of oscillations and collisions can populate the sterile neutrinos before BBN (see e.g., [38] and references therein). While in minimal See-Saw models the sterile neutrinos are too heavy to contribute to N_{eff} , several non-minimal scenarios (e.g., [39, 40]) include sterile neutrinos lighter than an eV.

Detailed studies exist on the effect of one sterile neutrino (ν_s from here on) on Y_p and N_{eff} (e.g. [37, 41, 42]). Here we consider one such case, assuming a hierarchical spectrum with the predominantly sterile state being the most massive, $\Delta m_{41}^2 \gg |\Delta m_{31}^2|$. Fig. 2 (adapted from the results of [42]) refers to the specific case in which ν_s mixes with ν_μ and ν_e , as needed to interpret the LSND anomaly [43]. It is however representative of the general situation. The four-neutrino mixing scheme can be reduced to an effective two-neutrino mixing with parameters $\Delta m_{LSND}^2 \simeq \Delta m_{41}^2 = m_4^2 - m_1^2$ and $\theta_{LSND} \simeq \theta_{es}\theta_{\mu s}$ [41] (Figure 2 refers to the case $\theta_{LSND}^{1/2} \simeq \theta_{es} \simeq \theta_{\mu s}$, which is conservative in that it generally corresponds to minimizing the high Y_p region, see [42].).

We consider both sterile neutrinos with and without lepton asymmetry, and we comment on the case of zero asymmetry first. In the plot we highlight the region of interest: the area (light shaded in the plot) where ν_s

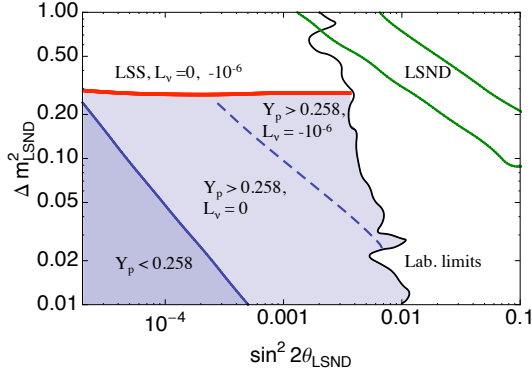


FIG. 2: Limits on the sterile neutrino oscillation parameters Δm_{LSND}^2 (in eV^2) and θ_{LSND} from several neutrino experiments and from the cosmological bound $\Omega_\nu h^2 < 0.006$. The shaded regions are allowed. For zero asymmetry, the dark (light) shaded area corresponds to $Y_p < 0.258$ ($Y_p > 0.258$). The dashed line represents the boundary of the $Y_p > 0.258$ region for asymmetry $L_\nu = -10^{-6}$. The region favored by the LSND data, now almost entirely excluded, is shown as well. See text for details.

is produced abundantly prior to BBN, thus causing a high Y_p via its contribution to the energy density, and contributing to N_{eff} at matter radiation-decoupling. Specifically, the region corresponds to $Y_p \geq 0.258$ and $N_{eff} = 3.8 - 4$, i.e., a nearly or completely populated sterile state. It is bounded from below by the “thermalization line”, where the ν_s production rate is comparable to the cosmic expansion rate [44]. and spans more than an order of magnitude in each parameter, extending down to $\sin^2 2\theta_{LSND} \sim 10^{-5}$. The region is constrained in mixing by several terrestrial experiments (mainly Karmen, Bugey, SuperK, CDHS [45–48] [68] and in Δm_{LSND}^2 by the cosmological bound on Ω_ν . For $N_{eff} = 4$, this bound gives:

$$\Delta m_{41}^2 \lesssim 0.28 \text{ eV}^2 \quad m_4 \lesssim 0.53 \text{ eV} , \quad (3)$$

assuming, conservatively, $m_1 \simeq m_2 \ll m_3 \simeq 0.05 \text{ eV}$, as given by oscillation data for the normal mass hierarchy [5]. We stress that the area we are considering was interpreted as excluded by BBN until recently. Our new perspective reopens this possibility.

Results similar to those in fig. 2 are obtained for other active-sterile mixing scenarios, such as those in which ν_s mixes with one active flavor or with one neutrino mass eigenstate. The mixing of ν_s with ν_3 is the least constrained because of the strong constraint on the ν_e component of ν_3 [41].

In the presence of lepton asymmetry, the production of sterile neutrinos via oscillations is suppressed

[42, 49–51]. This effect is due to the term in the potential describing neutrino-neutrino forward scattering, which suppresses the active-sterile mixing for neutrinos or antineutrinos and is zero for a symmetric neutrino population. Fig. 2 shows how the high Y_p region changes with the increase of L_ν which is assumed to be equal for all flavors. As a result of the suppression, with lepton asymmetry the region of high Y_p is reduced to a smaller area at high Δm_{LSND}^2 (fig. 2) and eventually disappears for $L_\nu \simeq 10^{-5}$ [42] as the mass required to populate the sterile neutrino becomes excluded by the bound on Ω_ν . Thus, a single light sterile neutrino can give only a subset of the region in our fig. 1. This subset has $3 \leq N_{eff} \leq 4$, with $N_{eff} \simeq 4$ being realized only for $\xi_{\nu_e} \simeq 0$.

The conclusions on the suppression of the production of ν_s are generally true for a wide range of lepton asymmetry, $L_\nu \sim 10^{-5} - 1$, provided that the asymmetry is constant over the characteristic time scale of the sterile neutrino production. For $L_\nu \sim 0.1 - 1$ the presence of the sterile state can modify Y_p through a modification of the spectra of the active states, while not affecting N_{eff} [24, 52, 53]. Therefore we do not consider this scenario here. A more diverse phenomenology is expected if the asymmetry varies over the time of ν_s generation: active-sterile oscillations can actually generate an asymmetry in the active flavors that can survive and affect the weak reaction rates [54, 55]. Although an updated analysis on this is not available, from existing studies [51] we infer that if the sterile neutrino contributes substantially to N_{eff} , and therefore its mass is below the LSS bound, the generated asymmetry is $L_\nu \lesssim 10^{-2}$, not sufficient to impact Y_p via BBN reaction rates. Therefore, this effectively reduces to the case $L_\nu = 0$.

If the neutrino mass arises from a Dirac mass term only, the right handed neutrino(s) associated to it are not produced via oscillations from the active states and therefore do not play the role of sterile neutrinos as described above. Still, a number of models exist in which right handed neutrinos are of sub-eV mass, and couple to the Standard Model particles strongly enough to be populated substantially prior to BBN [11, 56, 57]. A detailed analysis in the context of an E_6 symmetry [57] shows how, indeed, increased N_{eff} and Y_p are expected due to the right handed neutrino production. Compatibility with BBN translates into lower limits on the mass of the Z' . These limits will be relaxed for increased N_{eff} and Y_p ; the new expected mass range will be close to or overlap with the limits from SN1987A [58], and therefore measurements from a future galactic supernova could test such class of models, as we describe below.

EXPERIMENTAL SIGNATURES

A sterile neutrino with parameters in our high Y_p region has a number of implications for future detectors.

Beta decay and neutrino-less double beta decay experiments, designed to measure the neutrino mass, would probe a fourth light mass state that mixes with the electron neutrino (see e.g. [59]). The next generation of reactor neutrino experiments will probe this region beyond the existing limits, to an extent that depends on the specific model and on θ_{13} [60]. Neutrino beams will also allow to search for sterile states, probing different parameters depending on their energy and baseline [61]. For a ~ 10 GeV beam and $\Delta m_{41}^2 \lesssim 0.1$ eV², a baseline of $L \sim 2\pi E / \Delta m_{41}^2 \gtrsim 100$ Km is required. Signatures of a sterile state would be disappearance of the active flavors and anomalous differences in the oscillation pattern of neutrinos and antineutrinos due to refraction in the Earth. A recent example of the latter involves a sterile neutrino with parameters in our region of interest (high Y_p and high N_{eff}) [62], and is still interesting in the light of the hint of neutrino-antineutrino differences at MINOS [63].

It was observed [42] that the suppression produced by an asymmetry relaxes the cosmological bound on Δm_{LSND}^2 , thus allowing parameters that explain the LSND anomaly. As fig. 2 clarifies, however, these parameters correspond to low Y_p and $N_{eff} \simeq 3$ (the sterile state is not populated). Therefore, if MiniBOONE confirms LSND and high N_{eff} and Y_p are established, less minimal scenarios, beyond a CP-symmetric system of four neutrinos, would have to be considered.

Important astrophysical tests of a light sterile neutrino would come from atmospheric neutrinos and a future supernova neutrino detection [69]. Higher precision measurements of atmospheric neutrinos would extend the currently probed region of parameters. The detection of 0.1-1 TeV atmospheric neutrinos at IceCUBE would facilitate searches of sterile neutrinos in the higher Δm^2 range of our region, for which the active-sterile mixing is enhanced by matter effects [64, 65].

In a supernova, a sterile neutrino in our high Y_p region could be produced via resonant oscillations and cause a suppression of the active neutrino signal. Due to partial violation of adiabaticity [38, 41], the suppression would be moderate, at the level of tens of per cent. It will be detectable with a future galactic supernova if precise theoretical predictions of supernova neutrino emission are available.

Compared to a sterile neutrino, a right handed neutrino would be more difficult to test experimentally, because it requires non-oscillation tests. A possibility is to look for the new gauge bosons that couple to the right handed states, at man made or cosmic acceler-

ators. Among the latter, the neutrino burst from a galactic supernova would be sensitive to the the production of right handed states via their effect on the cooling rate, as mentioned previously. Constraints on a right handed neutrino will be highly model-dependent.

If a high N_{eff} and high Y_p are confirmed and other data exclude extra neutrino species that can be populated before BBN, one would have to consider more finetuned scenarios like large and opposite neutrino asymmetries in the different flavors. This would indicate CP violation in neutrinos, with profound implications on our understanding of the lepton sector. While to uniquely trace back to a model that generates opposite asymmetries might not be possible, a large number of mechanisms that predict more natural, comparable, asymmetries would be disfavored. Note, however, that it would be very difficult to confirm this scenario independently, because direct CP violation experiments in the neutrino sector would not probe the CP violating effects of relevance during BBN. Therefore precision cosmology alone might be required to more firmly constrain the neutrino sector.

Precision cosmological tests may be possible in the not-too-distant future. Direct kinematic constraints on neutrino masses from large scale structure tests, in particular from probes of galaxy clustering via the Sunyaev-Zeldovich effect on CMB, as currently being explored in the South Pole telescope [66, 67] could improve existing mass constraints by a factor of 2-5. At the same time, the Planck satellite will improve constraints on N_{eff} by increased sensitivity to high- l CMB anisotropies. Finally, direct measurements of primordial Y_p might be possible in the more distant future if spectral sensitivity to the CMB can be improved by several orders of magnitude.

To conclude, if the tentative new results on N_{eff} and Y_p are confirmed, they open up new possibilities for neutrino physics which may be accessible in the future by ground-based experiments and astrophysical probes. Specifically we find:

- A new relaxed constraint on possible electron neutrino asymmetry $-0.14 \lesssim \xi_{\nu_e} \lesssim 0.12$,
- if $N_{eff} \approx 4$, a bound $\Delta m_{41}^2 \lesssim 0.28$ eV², $m_4 \lesssim 0.53$ eV on sterile neutrino masses under fairly conservative assumptions about a mass hierarchy
- a new quantitative relation between the effects of possible independent variations in ξ_{ν_e} and N_{eff} on Y_p .
- a new set of possible astrophysical and experimental signatures that might further probe these scenarios

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- [1] P. J. Kernan and L. M. Krauss, *Phys. Rev. Lett.* **72**, 3309 (1994).
 - [2] G. Steigman, D. N. Schramm, and J. E. Gunn, *Phys. Lett.* **B66**, 202 (1977).
 - [3] H.-S. Kang and G. Steigman, *Nucl. Phys.* **B372**, 494 (1992).
 - [4] Y. I. Izotov and T. X. Thuan, *Astrophys. J.* **710**, L67 (2010), 1001.4440.
 - [5] K. Nakamura et al. (Particle Data Group), *J. Phys. G* **37**, 043509 (2010).
 - [6] E. Aver, K. A. Olive, and E. D. Skillman, *JCAP* **1005**, 003 (2010), 1001.5218.
 - [7] E. Komatsu et al. (WMAP), *Astrophys. J. Suppl.* **180**, 330 (2009), 0803.0547.
 - [8] E. Komatsu et al. (2010), 1001.4538.
 - [9] G. Steigman (2010), 1008.4765.
 - [10] G. Steigman, *JCAP* **1004**, 029 (2010), 1002.3604.
 - [11] K. A. Olive, G. Steigman, and T. P. Walker, *Phys. Rept.* **333**, 389 (2000), astro-ph/9905320.
 - [12] G. Steigman, *Ann. Rev. Nucl. Part. Sci.* **57**, 463 (2007), 0712.1100.
 - [13] C. J. Smith and G. M. Fuller, *Phys. Rev.* **D81**, 065027 (2010), 0905.2781.
 - [14] V. Barger, J. P. Kneller, P. Langacker, D. Marfatia, and G. Steigman, *Phys. Lett.* **B569**, 123 (2003), hep-ph/0306061.
 - [15] V. Barger, J. P. Kneller, H.-S. Lee, D. Marfatia, and G. Steigman, *Phys. Lett.* **B566**, 8 (2003), hep-ph/0305075.
 - [16] V. A. Kuzmin, V. A. Rubakov, and M. E. Shaposhnikov, *Phys. Lett.* **B155**, 36 (1985).
 - [17] J. A. Harvey and E. W. Kolb, *Phys. Rev.* **D24**, 2090 (1981).
 - [18] A. Casas, W. Y. Cheng, and G. Gelmini, *Nucl. Phys.* **B538**, 297 (1999), hep-ph/9709289.
 - [19] J. March-Russell, H. Murayama, and A. Riotto, *JHEP* **11**, 015 (1999), hep-ph/9908396.
 - [20] J. McDonald, *Phys. Rev. Lett.* **84**, 4798 (2000), hep-ph/9908300.
 - [21] M. Kawasaki, F. Takahashi, and M. Yamaguchi, *Phys. Rev.* **D66**, 043516 (2002), hep-ph/0205101.
 - [22] P.-H. Gu (2010), 1005.1632.
 - [23] P. D. Serpico and G. G. Raffelt, *Phys. Rev.* **D71**, 127301 (2005), astro-ph/0506162.
 - [24] K. Abazajian, N. F. Bell, G. M. Fuller, and Y. Y. Y. Wong, *Phys. Rev. D* **72**, 063004 (2005).
 - [25] J. P. Kneller and G. Steigman, *New J. Phys.* **6**, 117 (2004), astro-ph/0406320.
 - [26] V. Simha and G. Steigman, *J. Cosmol. Astropart. Phys.* **0808**, 011 (2008), hep-ph/0806.0179.
 - [27] J. P. Kneller, R. J. Scherrer, G. Steigman, and T. P. Walker, *Phys. Rev. D* **64**, 123506 (2001).
 - [28] C. Lunardini and A. Y. Smirnov, *Phys. Rev.* **D64**, 073006 (2001), hep-ph/0012056.
 - [29] Y. Y. Y. Wong, *Phys. Rev. D* **66**, 025015 (2002).
 - [30] K. N. Abazajian, J. F. Beacom, and N. F. Bell, *Phys. Rev. D* **66**, 013008 (2002).
 - [31] A. D. Dolgov, S. H. Hansen, S. Pastor, S. T. Petcov, G. G. Raffelt, and D. V. Semikoz, *Nucl. Phys. B* **632**, 363 (2002).
 - [32] S. Pastor, T. Pinto, and G. G. Raffelt, *Phys. Rev. Lett.* **102**, 241302 (2009), 0808.3137.
 - [33] C. J. Smith, G. M. Fuller, and M. S. Smith, *Phys. Rev.* **D79**, 105001 (pages 10) (2009).
 - [34] A. Cuoco, J. Lesgourgues, G. Mangano, and S. Pastor, *Phys. Rev.* **D71**, 123501 (2005), astro-ph/0502465.
 - [35] P. D. Serpico and G. G. Raffelt, *Phys. Rev.* **D70**, 043526 (2004), astro-ph/0403417.
 - [36] E. Holtmann, M. Kawasaki, K. Kohri, and T. Moroi, *Phys. Rev.* **D60**, 023506 (1999), hep-ph/9805405.
 - [37] J. Hamann, S. Hannestad, G. G. Raffelt, I. Tamborra, and Y. Y. Y. Wong (2010), 1006.5276.
 - [38] A. Y. Smirnov and R. Zukanovich Funchal, *Phys. Rev.* **D74**, 013001 (2006), hep-ph/0603009.
 - [39] A. de Gouvea, *Phys. Rev.* **D72**, 033005 (2005), hep-ph/0501039.
 - [40] A. de Gouvea, J. Jenkins, and N. Vasudevan, *Phys. Rev.* **D75**, 013003 (2007), hep-ph/0608147.
 - [41] M. Cirelli, G. Marandella, A. Strumia, and F. Vissani, *Nucl. Phys.* **B708**, 215 (2005), hep-ph/0403158.
 - [42] Y.-Z. Chu and M. Cirelli, *Phys. Rev.* **D74**, 085015 (2006), astro-ph/0608206.
 - [43] A. Aguilar et al. (LSND), *Phys. Rev.* **D64**, 112007 (2001), hep-ex/0104049.
 - [44] K. Enqvist, K. Kainulainen, and M. J. Thomson, *Nucl. Phys.* **B373**, 498 (1992).
 - [45] CDHS collaboration, *Phys. Lett.* **134B**, 281 (1984).
 - [46] Y. Declais et al., *Nucl. Phys.* **B434**, 503 (1995).
 - [47] B. Armbruster et al. (KARMEN), *Phys. Rev.* **D65**, 112001 (2002), hep-ex/0203021.
 - [48] S. Fukuda et al. (Super-Kamiokande), *Phys. Rev. Lett.* **85**, 3999 (2000), hep-ex/0009001.
 - [49] A. D. Dolgov and F. L. Villante, *Nucl. Phys.* **B679**, 261 (2004), hep-ph/0308083.
 - [50] R. Foot and R. R. Volkas, *Phys. Rev. Lett.* **75**, 4350 (1995).
 - [51] R. Foot and R. R. Volkas, *Phys. Rev.* **D55**, 5147 (1997), hep-ph/9610229.
 - [52] C. T. Kishimoto, G. M. Fuller, and C. J. Smith, *Phys. Rev. Lett.* **97**, 141301 (2006), astro-ph/0607403.
 - [53] C. J. Smith, G. M. Fuller, C. T. Kishimoto, and K. N. Abazajian, *Phys. Rev.* **D74**, 085008 (2006), astro-ph/0608377.
 - [54] R. Foot, M. J. Thomson, and R. R. Volkas, *Phys. Rev.* **D53**, R5349 (1996), hep-ph/9509327.
 - [55] X.-D. Shi, *Phys. Rev.* **D54**, 2753 (1996), astro-ph/9602135.
 - [56] G. Steigman, K. A. Olive, and D. N. Schramm, *Phys. Rev. Lett.* **43**, 239 (1979).
 - [57] V. Barger, P. Langacker, and H.-S. Lee, *Phys. Rev.* **D67**, 075009 (2003), hep-ph/0302066.

- [58] R. Barbieri and R. N. Mohapatra, Phys. Rev. **D39**, 1229 (1989).
- [59] S. Goswami and W. Rodejohann, Phys. Rev. **D73**, 113003 (2006), hep-ph/0512234.
- [60] A. de Gouvea and T. Wytock, Phys. Rev. **D79**, 073005 (2009), 0809.5076.
- [61] A. Dighe and S. Ray, Phys. Rev. **D76**, 113001 (2007), 0709.0383.
- [62] N. Engelhardt, A. E. Nelson, and J. R. Walsh, Phys. Rev. **D81**, 113001 (2010), 1002.4452.
- [63] A. A. Aguilar-Arevalo et al. (The MiniBooNE) (2010), 1007.1150.
- [64] H. Nunokawa, O. L. G. Peres, and R. Zukanovich Funchal, Phys. Lett. **B562**, 279 (2003), hep-ph/0302039.
- [65] S. Choubey, JHEP **12**, 014 (2007), 0709.1937.
- [66] J. E. Carlstrom, P. A. R. Ade, K. A. Aird, B. A. Benson, L. E. Bleem, S. Busetti, C. L. Chang, E. Chauvin, H. Cho, T. M. Crawford, et al., ArXiv e-prints (2009), 0907.4445.
- [67] J. Ruhl, P. A. R. Ade, J. E. Carlstrom, H. Cho, T. Crawford, M. Dobbs, C. H. Greer, N. w. Halverson, W. L. Holzapfel, T. M. Lanting, et al., in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, edited by C. M. Bradford, P. A. R. Ade, J. E. Aguirre, J. J. Bock, M. Dragovan, L. Duband, L. Earle, J. Glenn, H. Matsuhara, B. J. Naylor, H. T. Nguyen, M. Yun, & J. Zmuidzinas (2004), vol. 5498 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, pp. 11–29, arXiv:astro-ph/0411122.
- [68] The recent MiniBooNE results [63] are not yet competitive with older limits, due to low statistics.
- [69] Bounds from solar neutrinos refer to lower sterile masses, $\Delta m_s^2 \lesssim 10^{-4} \text{ eV}^2$, so they do not apply to the hierarchical mass scenario that we discuss here.